

Transition of NDEAA Related Technology to Planetary Telerobotic Mechanisms at JPL

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ABSTRACT

Jet Propulsion Laboratory (JPL) is responsible for the NASA unmanned deep space exploration programs. In recent years, JPL has become increasingly involved with in-situ planetary exploration tasks where miniature, miser, light and inexpensive telerobotic mechanisms are needed. These tasks are conducted at harsh temperature and pressure conditions that are challenging the limits of existing technologies. Addressing these needs for effective NDE and advanced actuators (NDEAA) to support planetary systems is the objective of the R&D efforts of the JPL's NDEAA Technologies team. Various wave modes and electroactive materials are being investigated to develop devices, methodologies, and mechanisms to address these needs. This effort involves cooperation with scientists and engineers at various organizations that include universities, research institutes, government organizations and industry in the US and abroad. The team's initial effort was focused on the development of NDE techniques using the ultrasonic Leaky Lamb Waves (LLW) and Polar Backscattering. In the last 7 years, these efforts have evolved to development of actuation, robotics, geophysics, medicine and others using ultrasonics, piezoelectrics and electroactive materials.

INTRODUCTION

The JPL's NDEAA Technologies laboratory [<http://ndeaa.jpl.nasa.gov>] was established in 1991 and started with emphasis on research and development of nondestructive evaluation technologies. The author's discovered leaky Lamb wave and polar backscattering phenomena in composite materials were investigated towards transition to practical NDE methodologies. Later, the NDEAA team activity has evolved to developing broad range of mechanisms and devices taking advantage of the acoustic or elastic waves and their source capabilities. These efforts cover a wide spectrum of frequencies and amplitudes as shown in table 1. The mechanisms and devices that are developed by NDEAA include ultrasonic motors and piezopumps that are driven by traveling flexural waves. Using a piezoelectric stack actuator, an ultrasonic driller and corer is being developed potentially applicable at high temperatures as expected on Venus and low temperatures as on Mars. In parallel, electroactive polymers are being investigated for use as actuators that are acting like muscles earning them the name artificial muscles. A dust wiper driven by these materials is being developed operating similar to an automobile windshield wiper but with a very simple mechanism. In addition, the team is also involved with the exploration of ultrasonic methods for medical diagnostics and treatment applications.

TABLE 1: NDEAA technologies categorized by the acoustic and elastic wave frequency and amplitude range.

| | <i>Low amplitude</i> | <i>High amplitude</i> |
|-----------------------------------|----------------------|----------------------------|
| Low frequency (Hz - KHz) | Sonotomography | Actuation, drilling/coring |
| High frequency (KHz - MHz) | NDE & diagnostics | Medical treatment |

NONDESTRUCTIVE EVALUATION (NDE) METHODS

Ultrasonic Oblique Insonification Techniques

Two ultrasonic oblique insonification phenomena were discovered in composite materials by the author including leaky Lamb wave (LLW) [Bar-Cohen and Chimenti, 1984] and Polar Backscattering [Bar-Cohen and Crane, 1982]. The phenomena are studied jointly by the author and his coinvestigators to establish effective NDE methods for composite materials [Bar-Cohen, Mal, and Lih, 1993]. The focus on composites has been the result of the recognition that one of the limiting factors in the widespread use of composites is their high cost. Composite parts are about an order of magnitude more expensive than metallic parts and approximately 30% of this cost is for inspection. This large portion of the total cost makes the need for effective inspection critical not only for operational safety but also for the cost effectiveness of these materials [Bar-Cohen, et al, 1991].

The polar backscattering, which was first observed in July 1979, found application mostly as a qualitative tool for the detection of such flaws as porosity. On the other hand LLW, which was first observed in August 1982, has been studied extensively towards developing a quantitative methodologies. LLW are induced by oblique insonification using a pitch-catch arrangement and the resulting modes are acquired by identifying minima in the reflected spectra. These modes are recorded in the form of dispersion curves, which are evaluated in relation to analytical data. The wave behavior in multi-orientation laminates was modeled and corroborated experimentally with high accuracy. The sensitivity of the wave to the elastic constants of layered materials and to the boundary conditions enabled the measurement of the elastic properties of bonded joints. To support the need for an effective data acquisition setup a LLW scanner (see Figure 1) was developed as a C-Scan attachment (jointly with QMI). In time, the LLW data acquisition experimental capability was significantly improved increasing the acquisition speed to the level of a fraction of a minute as well as greatly increasing the number of modes that can be identified [Bar-Cohen and Lih, 1999]. This capability greatly increased the accuracy of the data inversion, improved the capability to characterize flaws and the practicality of the technique.



FIGURE 1: A view of the LLW scanner (bridge right side) installed on the JPL's C-scan system.

To enhance the inversion accuracy of the material stiffness constants, a method was developed to acquire dispersion curves and display them as shown in Figure 2. This Figure is showing the dispersion curve for a 3.125-mm unidirectional laminate that was tested along the fibers. This method was found to allow viewing modes with amplitude levels that are

significantly smaller than observed ever before. The bright curved lines show the modes on the background of the reflected spectra. Using this capability the unidirectional laminate was also tested along the 90° polar angle. As can be seen in Figure 3, modes that otherwise would be considered noise are clearly identified.

FIGURE 2: A view of the LLW dispersion curve for unidirectional Gr/Ep along the fibers using an imaging approach.

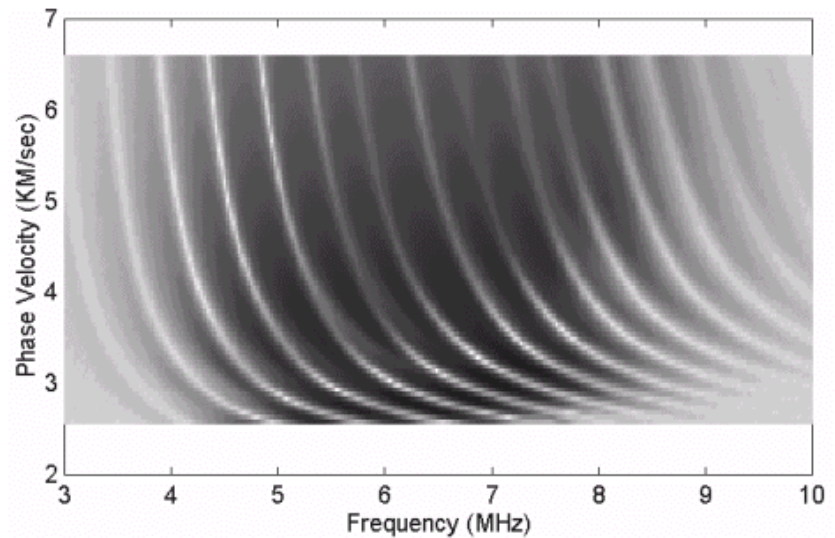
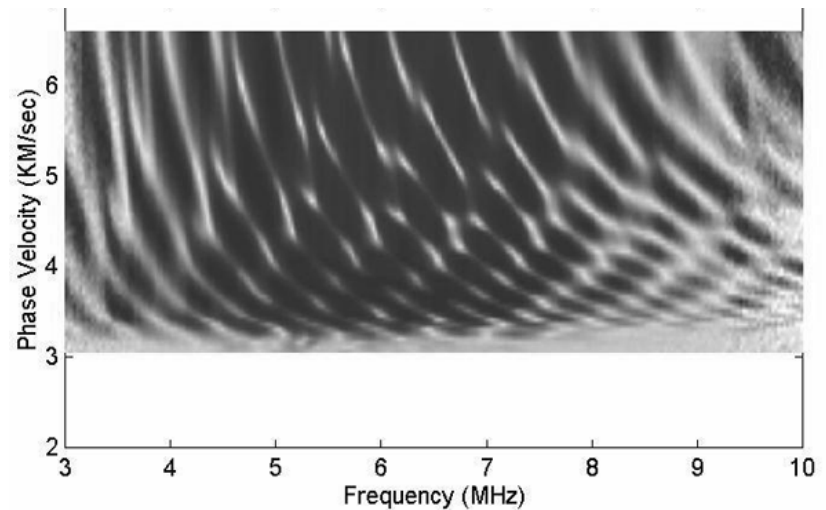


FIGURE 3: A view of the dispersion curve for the laminate shown in Figure 2 along the 90° polar angle.



Open-architecture robotic crawlers for NDE of aircraft structures

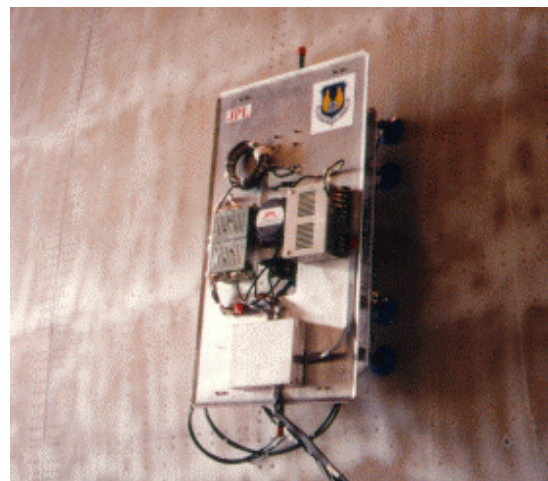
Rapid inspection of large areas has been an ongoing challenge to the NDE engineering community [Bar-Cohen, 2000]. The need for such a capability grew significantly in recent years as a result of the increase in the numbers of aging aircraft in service and of aircraft with composite primary structures. While aging aircraft with metallic structures are susceptible to corrosion and cracking, mostly near fastener areas, composites are sensitive to impact damage that can appear anywhere on the structure. Field inspection using manual scanning is labor intensive, time consuming and subjected to human error, whereas removal of parts from an aircraft for a lab test is costly and may not be practical. Effective field inspection requires a portable, user friendly system that can rapidly scan large areas of complex structures. In recent years, various portable inspection systems have emerged including scanners that are placed at selected locations and sequentially repositioned to fully cover the desired areas. The development of such systems followed the

technology evolution and it requires integration of multidisciplinary expertise including NDE, telerobotics, neural networks, automated control, imbedded computing and materials science. The overall evolution has been towards full automation and there is a desire to have a completely autonomous inspection capability.

Scanning an aircraft using a portable bridge configuration has been an effective step in addressing the need for automatic field testing capability. However, the constraint to covering an area only within the bounds of the scanner-bridge has limited the operation speed, the accessibility to complex areas (particularly near joint with a wing, etc.) and required scaffolding to allow sequential attachment of the bridge to different locations. Mobile scanners can greatly increase the rate of inspection, minimize human errors and offer flexibility of reaching various areas of the aircraft. These scanners need to have a controlled adherence capability to maintain attachment to the structure surface while traveling and inspecting it. Such scanners, in the form of crawlers, are increasingly emerging as a solution to the need for unconstrained mobility and dexterity while conducting automatic scanning. The use of suction cups has become a leading form of controlled adherence to aircraft surfaces and several successful scanners have developed in the last several years. The Automated Non Destructive Inspector (ANDI) and the Autocrawler are some of the more known mobile scanners [Bahr, 1992; Backes & Bar-Cohen, 1996; and Siegel, et al, 1998].

In recognition of the need to have a compact, more maneuverable crawler, JPL recently developed a small, highly dexterous crawler so-called Multifunction Automated Crawling System (MACS). This crawler, which is shown in Figure 4, was designed to perform complex scanning tasks [Backes & Bar-Cohen, 1996; and Bar-Cohen and Backes, 1999] taking advantage of its ability to easily turn or move forward and backward while being attached to a curved surface. A schematic view of MACS traveling and rotating while activating its legs and suction cups is shown in Figure 5 and from different angle views are shown in Figure 6. MACS employs ultrasonic motors for mobility and suction cups for surface adherence. It has two legs for linear motion, with one of the legs serving as the rotation element for turning. The ability to crawl on surfaces has been enabled by use of suction cup elements that are extended at the stage of attachment. An air pressure is used to eject the suction cups onto the test surface at the moment that the specific leg is made to adhere to the surface. Individual venturi pumps provide each suction cup with sufficient vacuum to assure effective attachment. The ability to adjust the ejection distance of the individual rods allows the crawler to travel on curved surfaces. The smallest diameter of the curved surface, which can be inspected by MACS, depends on the suction cups total ejection length and the size of the crawler platform. This mobility configuration allows performing any simultaneous combination of motion, including linear travel as well as rotation around the central axis.

FIGURE 4: MACS crawling on the C-5 aircraft
[Bar-Cohen, Joffe, and Backes, 1999].



The development of MACS was benefited from the ongoing JPL development of miniature planetary rovers as well as telerobotic and NDE techniques. MACS was developed to serve as a generic open architecture robotic platform that can be used for many applications, including inspection, paint removal and painting of ships as well as testing/maintaining aircraft. Having many users is expected to lead to lower cost systems that will be improved by a large pool of users and developers. The monitoring of MACS activities can be designed for local control or control via the Internet with password access. This crawler established the foundations for the development of a "walking" computer platform with standard plug-in NDE boards. A standard PC architecture will enable rapid implementation of new sensors, which can be easily integrated into the setup. To define the crawler functions, plug-and-play boards will need to be developed and thus enable a new NDE industry that can rapidly introduce novel products as well as transfer technology to commercial use. This capability will allow a larger pool of companies and individuals to become potential producers of NDE instruments. Thus, a significant cost reduction can be materialized with a rapid transition of novel concepts to practical use. The JPL's telerobotic program and extensive planetary exploration experience with rover technology can provide a valuable resource to this emerging and enabling technology.

FIGURE 5: MACS crawler mobility control. Solid circles represent activated suction cups and hollow circles represent resting cups. Forward travel is shown on the left and a simultaneous travel/rotation is shown on the right.

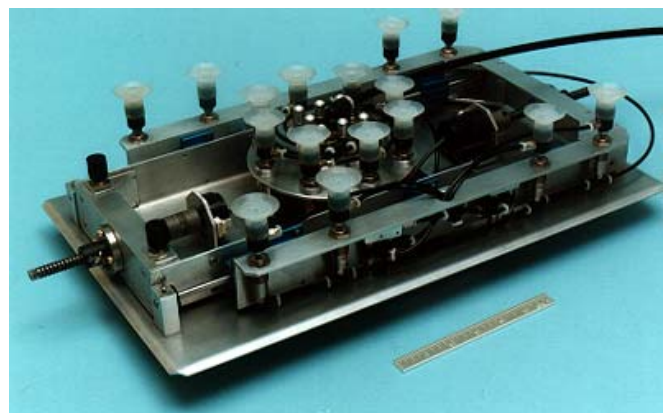
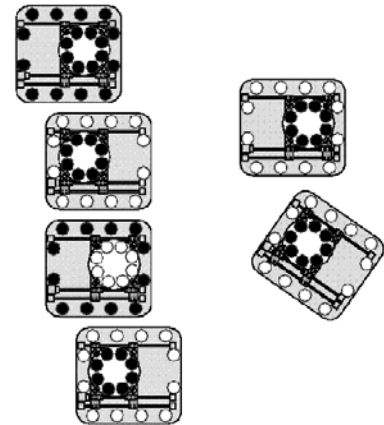


FIGURE 6: A photographic view of MACS from difference angles, where the two legs and the crawler ability to be attached to a curved surface are shown.

Ultrasonic Medical Diagnostics and Treatment

Ultrasonic technology emerged as a medical diagnostic technology in the late 1960's and the field of obstetrics has been one of the first applications [Sunden, 1967]. The most widely used techniques today are pulsed echo (2.0 to 7.0 MHz) and Doppler imaging (2 to 4 MHz). Currently used equipment offers real-time imaging, where the moving fetus is viewed on a color monitor. Pulse echo techniques are employed with the transducer coupled either in contact, immersion or using a liquid delay line. To obtain instant images, a transducer array is used and the reflected signals are monitored. The sensitivity and resolution have been improved to a level that allows viewing of even the movements of the fetal heart, and to conduct accurate measurements on the monitor. Such measurements form the cornerstone of the assessment of fetal gestational age, size and health. Progressively, ultrasonics has become an indispensable tool for many medical diagnostic applications. It has a vital role in the assessment of pregnant woman, in patients with heart disease, stroke and disorders of the vascular system, and in imaging of other vital organs such as the liver, kidneys, as well as the abdomen and soft tissues. This capability allows the examination of atherosclerosis and other disease processes. The development of real-time imaging with the selectable combination of color hues onto shades of gray has added a powerful imaging capability for viewing subtle tissue details. This enhancement provides a better interpretation of the ultrasonic images. The use of 3-D imaging is being developed for volumetric measurements as well as to enhance image interpretation and presentation.

The application of high power ultrasonics for medical treatment was first introduced as a lithotripsy tool for the dissolution of kidney stones, and became a practical method in the late 1970s [Segura, 1990]. Generally, high intensity focused ultrasonic waves can be used to conduct various transcutaneous (through the skin) medical treatments. The principle that makes high intensity ultrasound an effective tool is the induction of shock-waves as a result of forming cavitation bubbles that implasively collapse. The cavitations are formed when the pressure associated with the wave (at the rarefaction phase) drops below the vapor pressure of the liquid in which the wave propagates. The implosion, i.e. collapse inward, of cavitation occurs mostly when the wave cycle turns to the compression phase and it induces shock waves. The larger the cavitation bubble, the more violent is its collapse, and the more effective its eroding effect. However, the requirement for large wavelengths is subject to diffraction limits causing difficulties in focusing the wave. The author in cooperation with QMI and Cedars Sinai Medical Center developed a novel Focused Modulated High Power Ultrasound (FMPUL) device [Grandia and Bar-Cohen, 1998]. This FMPUL device (shown in Figure 7) allows modulation of LF and HF forming large and effective cavitation in a constrained focal zone. High power ultrasonic waves induce a variety of effects that can be useful tools, including streaming which is a strong flow of the liquid, particularly at the focal spot (see Figure 8). Generally, ultrasound causes rapid and reversible damage to tissues making it attractive for various medical treatment requirements, including cancer.

Noninvasive Geophysical Probing System (NGPS)

The JPL's NDEAA team jointly with the University of Texas at El Paso (UTEP) are extensively involved in research and development of geophysical noninvasive probing methodologies using surface waves. These methodologies offer the capability to determine properties of ground layers without a complex inversion algorithm or mechanism drilling. To

implement the experimental procedure, a high-frequency source and two or more receivers are utilized. At wavelengths greater than the thickness of the individual layers, the velocity of propagation is independent of wavelength. The shear wave velocity of the layer can be obtained using a complex-valued curve-fitting process with the coherence as the weighing function [Nazarian et al., 1993]. The actual and fitted curves compare quite favorably and are used to "unwrap" the phase, where the appropriate number of cycles is added to each phase. Then the slope of the line, which is basically constant with frequency, is calculated and is used to quantitatively characterize the tested medium. Recently, the team used this method to develop a method of measuring the thickness of coal. The accuracy of estimating the thickness of a coal layer that has a soil or rock substrate was demonstrated to be about 10-15% [Nazarian and Bar-Cohen, 1999]. Such a capability is important for the coal mine industry who is seeking to automate their mine harvesting process and thus increasing the profitability and reduce the risk to human operators.



FIGURE 7: FMPUL transducer with center element transmitting at 20-KHz and focused 500KHz transmitter.



FIGURE 8: Streaming effect resulting from the focusing of about 800KHz onto the surface of water.

ADVANCED ACTUATORS

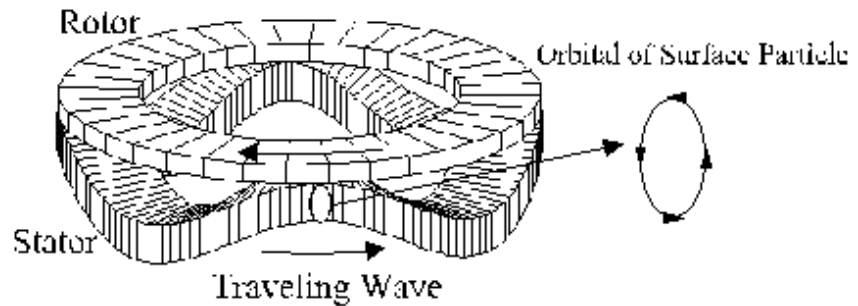
Ultrasonic motors

Efficient miniature actuators that are compact and consume low power are needed to drive space and planetary mechanisms in future NASA missions. Ultrasonic plate waves can be harnessed to provide actuation forces to produce ultrasonic motors that have the potential to meet NASA needs. Generally, ultrasonic motors [Wallashek, 1995] can be classified by their mode of operation (static or resonant), type of motion (rotary or linear) and shape of implementation (beam, rod, disk, etc.). Despite the distinctions, the fundamental principles of solid-state actuation tie them together: microscopic material deformations (usually associated with piezoelectric materials) are amplified through either quasi-static mechanical or dynamic/resonant means. Several of the motor classes have seen commercial application in areas needing compact, efficient, and intermittent motion. Such applications include camera auto-focus lenses, watch motors and compact paper handling. Obtaining the levels of torque-speed characteristics of

USMs using conventional motors requires adding a gear system to reduce the speed, thus increasing the size, mass and complexity of the drive mechanism. USMs are fundamentally designed to have a high holding force, providing effectively zero backlash. Further, since these motors are driven by friction the torque that would cause them to be backdriven at zero power is significantly higher than the stall torque. The number of components needed to construct ultrasonic motor is small minimizing the number of potential failure points. The general characteristic of USMs makes them attractive for robotic applications where small, intermittent motions are required.

In Figure 9 the principle of operation of an ultrasonic motor (flexural traveling wave ring-type motor) is shown as an example. A traveling wave is established over the stator surface, which behaves as an elastic ring, and produces elliptical motion at the interface with the rotor. This elliptical motion of the contact surface propels the rotor and the drive-shaft connected to it. Teeth on the top section of the stator are intended to form a moment arm to amplify the speed. The operation of USM depends on friction at the interface between the moving rotor and stator, which is a key issue in the design of this interface for extended lifetime.

FIGURE 9: Principle of operation of a rotary flexural traveling wave motor.



The use of USMs in NASA application requires operation at harsh space environments that include cryogenic temperatures and vacuum and also require effective analytical tools for the design of efficient motors. To explore telerobotic applications for USMs a robotic arm was constructed with such motors. A finite element analytical model was developed to examine the excitation of flexural plate wave traveling in a piezoelectrically actuated rotary motor [Bar-Cohen, et al, 1998]. The model uses 3D finite element and equivalent circuit models that are applied to predict the excitation frequency and modal response of the stator. This model incorporates the details of the stator including the teeth, piezoelectric ceramic, geometry, bonding layer, etc. The theoretical predictions were corroborated experimentally for the stator. In parallel, efforts have been made to determine the thermal and vacuum performance of these motors. Experiments have shown that the motor can sustain at least 230 temperature cycles from 0°C to -90°C at 7 Torr pressure significant performance change. Also, the motor lasted over 334 hours at -150°C and vacuum.

To examine the cause of failure, an ultrasonic C-scan nondestructive test was made and the discontinuities were imaged on the computer monitor. As anticipated, the bond between the stator and piezoelectric ring wafer failed. The continuous piezoelectric ring that drives the stator is subjected to thermal stresses that are aggravated by the cyclic mechanical loading of the motor operation leading to fatigue failure of the bond line. JPL in cooperation with QMI replaced the continuous ring with segmented and reversed piezoelectric drive (SRPD) wafers allowing to effectively relieve the thermal and dynamic stresses at the bonding layer.

Piezopump [<http://ndeaa.jpl.nasa.gov/>]

A simulation of the wave travel on the stator of an ultrasonic motor it is easy to the formation of valleys that are traveling. Covering these valleys allows forming chambers that can be used as boxcars to carry liquids operating as a peristaltic pump. Such piezopump eliminates the need for valves or physically moving parts and there is a range of NASA experiments, instruments and applications where such miniature pumps are needed. . Finite element model was developed using ANSYS for the purpose of predicting the resonance frequency of the vibrating modes of the piezopump driving stator. The model allows determining simultaneously the mode shapes that are associated with the various resonance frequencies. This capability is essential for the design the pump size and geometry. To predict and optimize the pump efficiency that is determined by the volume of pumping chambers the model was modified to perform harmonic analysis. Current capability allows the determination of the effect of such design parameters as pump geometry, construction materials and operating modes on the volume of the chambers that are formed between the peaks and valleys of the waves. Experiments were made using a piezopump breadboard showed water-pumping rate of about 1.8 cc/min. The pump is continually being modified to enhance the performance and efficiency. In Figure 10 a photograph shows a prototype piezopump pumping water.

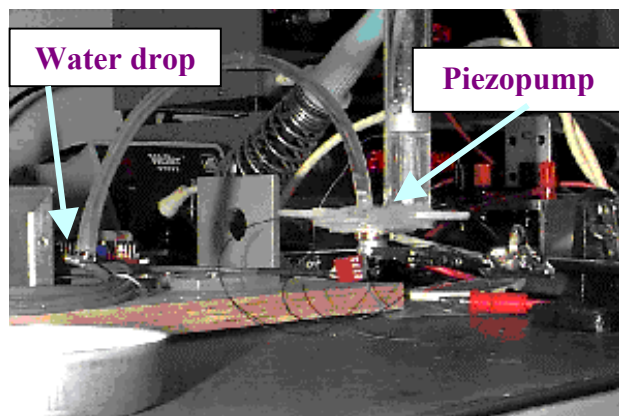


FIGURE 10: A view of piezopump in action.

Ultrasonic/Sonic Drilling/Coring (USDC)

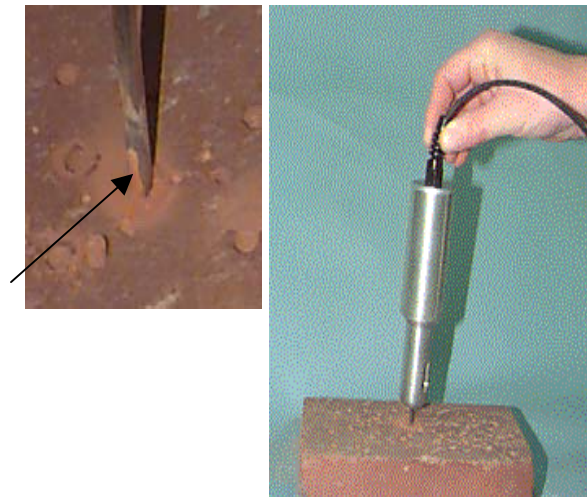
NASA's Mars and Solar System exploration missions are seeking to in-situ collect samples from the various depths of various planets. The environments that these instruments are expected to face range from cryogenic (Comets) to very hot and aggressive (Venus). Geological surveys from a lander or a rover require instrumented samplers to be placed at the end of a flexible arm or on a very-light rover. Low mechanical impact on the host is a major requirement for these samplers. Recently, a ultrasonic/sonic drilling/coring (USDC) mechanism was developed that potentially allows meeting key challenges of planetary *in situ* sampling [Sherrit, et al, 1999]. It requires low preload (<5N) and power and it was shown to drill various rocks including granite, where a 2.5" thick construction brick was drilled in 5 minutes. It has a debris self-extracting mechanism via an ultrasonic transport up the drilling shaft. USDC is highly tolerant to misalignment even during drilling. The drilling/coring bit does not turn, thus, *in-situ* sensors can be integrated into the bit and also one can safely touch the USDC bit with one's bare hand during operation. The device can potentially be used as a tool for future human habitation on Mars or other planets and it can be tailored for operation in the harsh environments of various planets.

The USDC uses a floating head mechanism, where high frequency ultrasonic vibrations induced by a piezoelectric stack are used to create a hammering action. The floating head is a

mechanical frequency transformer, and the drill bit operates with a combination of ultrasonic and sonic frequencies. This transformer converts the 20 kHz ultrasonic drive frequency to a combination of this high frequency drive signal and a 60-1000 Hz sonic hammering action. The drilling mechanism requires the simultaneous presence of both frequencies. Finite element modeling and experiments that include drilling and coring of various types of rocks are currently under way.

In Figure 11, the USDC is shown held from its power cord while drilling a brick - this is possible because relatively low axial preload is required. The non-criticality of alignment and the fact that the drilling debris is traveling along the core shaft away from the hole can also be easily seen in this Figure. As a result of the transverse and longitudinal motions involved with this drilling mechanism, the coring bit creates a hole that is slightly larger than the drill bit diameter. This reduces the chances of bit jamming if the integrity of the hole is maintained, thus avoiding the problem associated with conventional drilling. The USDC bit does not have to be sharp, and various drill bits can be designed to take advantage of this novel enabling technology.

FIGURE 11: The USDC mechanism uses vibration to create hammering action, where relatively small preload is required to create a core while holding the power cord. The device has shown drilling-debris removal capability along the drill bit.



Telepresence - Interactive and Intuitive Mirroring of Remote / Virtual Compliance and Forces

For many years, the robotic community sought to develop robots that can eventually operate autonomously and eliminate the need for human operators. However, there is an increasing realization that humans can perform some tasks significantly better but, due to associated hazards, distance, physical limitations and other causes, only robots can be employed to perform these tasks. Remotely performing such tasks by operating robots as human surrogates is referred to as telepresence. In telepresence the operator receives sufficient information about the remote robot and the task environment displayed in a sufficiently natural way, that the operator would be able to feel the equivalent of physical presence at the remote site. Haptic feedback is necessary for a telepresence system where physical constraints such as object rigidity, mass and weight, friction, dynamics, surface characteristics (smoothness or temperature) are mirrored to the human operator from the remote site.

Robots capability to operate as a surrogate human, has been recently implemented at NASA Johnson Space Center with the development of the novel space robot called Robonaut (see Figure 12) [<http://tommy.jsc.nasa.gov/robonaut/Robonaut.html>, 1997]. This robot is capable of performing various tasks at remote sites and serve as a robotic astronaut on the International Space Station, providing a relatively fast response time and the ability to maneuver through areas too small for the current Space Station robots. Robonaut is developed to support high-payoff

EVA tasks and to provide "minuteman"-like responses to extra-vehicular activity (EVA) contingencies. The Robonaut is designed as an anthropomorphic robot, similar in size to a suited EVA astronaut and as a telepresence system that immerses the remote operator into the robot's environment. The robotic arms are capable of dexterous, human-like maneuvers and are designed to ensure safety and mission success. The robotic hands are designed to handle common EVA tools, to grasp irregularly shaped objects, and to handle a wide spectrum of tasks requiring human-like dexterity. Robonaut was designed so that a human operator who is wearing gloves/suit with sensors can control it. If the user is to interact in a natural way with the robot, the interface must be intuitive, accurate, responsive, transparent and reproducible over time and space. Furthermore, the operator must be able to extract information about the robot and its environment to effectively control the robot. Unfortunately, due to unavailability of force and tactile feedback capability in the control suit/glove, the operator determines the required action by visual feedback, i.e. looking at the Robonaut action at the remote site. This approach is ineffective and is limiting the potential tasks that Robonaut can perform.

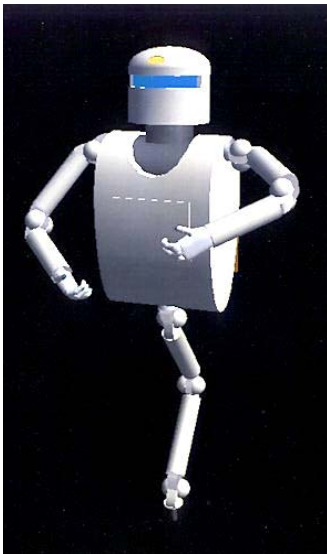


FIGURE 12 - Robonaut

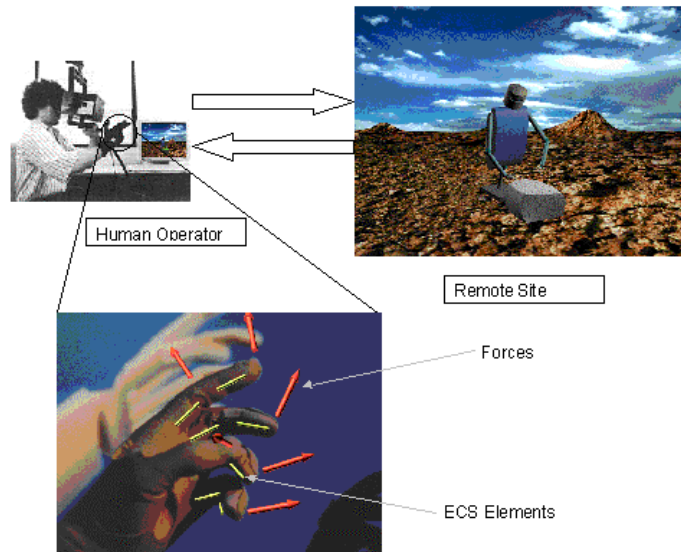


FIGURE 13 - Performing Remote Tasks via a Haptic Interface

To address the need for telepresence, a haptic interfacing mechanism is required to allow operators to "feel" the stiffness and forces at remote or virtual sites (See Figure 13). For this purposed the JPL's NDEAA has teamed with Rutgers University investigators and conceived a system that is called MEMICA (remote Mechanical Mirroring using Controlled stiffness and Actuators) [Bar-Cohen, Pfeiffer, Mavroidis & Dolgin, 1999.] The key aspect of the MEMICA system is a miniature Electrically Controlled Stiffness (ECS) element that mirrors the stiffness at remote/virtual sites. The ECS elements make use of Electro-Rheological Fluid (ERF), which is an Electro-Active Polymer (EAP), to achieve the feeling of remote or virtual stiffness. The ECS elements will be placed at selected locations of an instrumented glove to mirror the forces of resistance to motion at the corresponding locations of the robot hand. Forces applied at the robot end-effector due to a compliant environment will be reflected to the user with the aid of this ERF device where a change in the system viscosity will occur proportionally to the force to be transmitted. The MEMICA system also consists of Force Feedback Actuation Tendon (FEAT) elements, which employ other type of actuators to mirror forces induced by active elements at the remote or virtual site.

Electroactive Polymers Actuators - Artificial Muscles

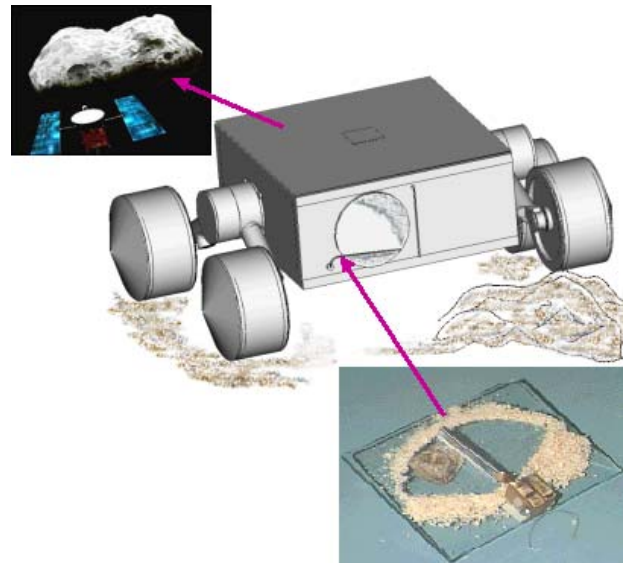
Biologically inspired mechanisms, such as snake robot, can be used to perform NDE and other tasks that are not possible with today technology. Such tasks include testing highly concealed areas of engines and aircraft fuselage and they require actuators that emulate biological muscles. The closest actuators that can fit this category are the electroactive polymers (EAP). For many years, EAP received relatively little attention due to the small number of available materials and their limited actuation capability. The recent emergence of EAP materials with large displacement response changed the paradigm of these materials and their potential capability [Bar-Cohen, 1999a]. The most attractive feature of EAPs is their ability to emulate biological muscles with high toughness, large actuation strain and inherent vibration damping. EAP can be used to produce highly maneuverable, noiseless and agile, with various shapes including insect-like. Effective EAP offers the potential of making science fiction ideas a faster reality than would be feasible with any other conventional actuation mechanisms. Unfortunately, the force actuation and mechanical energy density of EAPs are relatively low, limiting the potential applications that can be considered at the present time. To overcome this limitation there is a need for development in numerous multidisciplinary areas from computational chemistry, comprehensive material science, electromechanic analysis and improved material processing techniques. Efforts are needed to gain a better understanding of the parameters that control the electromechanical interaction. The processes of synthesizing, fabricating, electroding, shaping and handling need to be refined to maximize their actuation capability and robustness.

Under the author's lead, planetary applications using EAP are being explored while improving the understanding, practicality and robustness of these materials. EAP materials are sought as a substitution to conventional actuation components such as motors, gears, bearings, screws, etc. This research and development effort has been conducted since 1995 under the NASA task called Low Mass Muscle Actuator (LoMMAs), and the current team consists of JPL, NASA-LaRC, VT, Rutgers University, and ESLI having cooperative efforts with Osaka National Research Institute, Japan, and, Kobe University, Japan [Bar-Cohen, et al, 1999b]. Longitudinal and bending EAP are being investigated, and a dust-wiper, gripper and robotic arm were demonstrated [Bar-Cohen, et al, 1999c]. The dust-wiper (Figure 14) is currently being developed for the Nanorover's optical/IR window, which is part of the MUSES-CN mission. The MUSES-CN is a joint NASA and Japanese Space Agency mission scheduled for launch in January 2002, from Kagoshima, Japan, to explore the surface of a small near-Earth asteroid.

Generally, the practical application of EAP materials is still a great challenge. No effective and robust EAP material is currently available commercially. Further, there is no established database that documents the properties of the existing EAP materials. In recognition of the need for international cooperation among the developers, users and potential sponsors, an SPIE Conference was organized for the first time on March 1-2, 1999, in Newport Beach, California [Bar-Cohen, 1999a]. The conference was the largest ever on EAP, and it marked an important milestone, turning the spotlight onto these emerging materials and their potential. Following this success, an MRS conference was initiated to address fundamental issues related to the material science of EAP. As of 1999, the science and engineering community is offered two annual international conferences (SPIE and MRS) that are solely dedicated to the subject of EAP. The WW-EAP Newsletter (http://eis.jpl.nasa.gov/ndeaa/nasa-nde/newsltr/WW-EAP_Newsletter.PDF) was initiated and a homepage was formed linking worldwide EAP research and development websites (<http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm>). Also, government resources

are being devoted at unprecedented levels to sponsor research in this area. The increased research and the improved collaboration among the developers, users and sponsors are expected to foster progress at a significantly high rate.

FIGURE 14: Schematic view of the EAP dust-wiper on the MUSES-CN's Nanorover (right) and a photograph of a prototype EAP dust-wiper (left).



The author challenged the EAP community to develop robotic arms actuated by artificial muscles that would win an arm wrestling match with a human (Figure 15). Progress towards this goal will lead to great benefits, particularly in the medical area, including effective prosthetics. Decades from now, EAP may be used to replace damaged human muscles, leading to a "bionic human." A remarkable contribution of the EAP field would be to one day seeing a handicapped person jogging to the grocery store using this technology.

FIGURE 15: Grand Challenge for the EAP Community.



CONCLUDING REMARKS

Time dependent elastic motion offer diagnostics and actuation capabilities. The JPL's NDEAA team have taken waves and transmission source and developed novel capabilities to support various technology areas that include space, robotics, medical, etc. Finite element modeling tools and experimental capabilities were developed to support the required design tools. Development in NDE related activity include the LLW, MACS, NGPS and FMPUL and

in areas related to actuation activity include USM, Piezopump, MEMICA and various applications of electroactive polymers.

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